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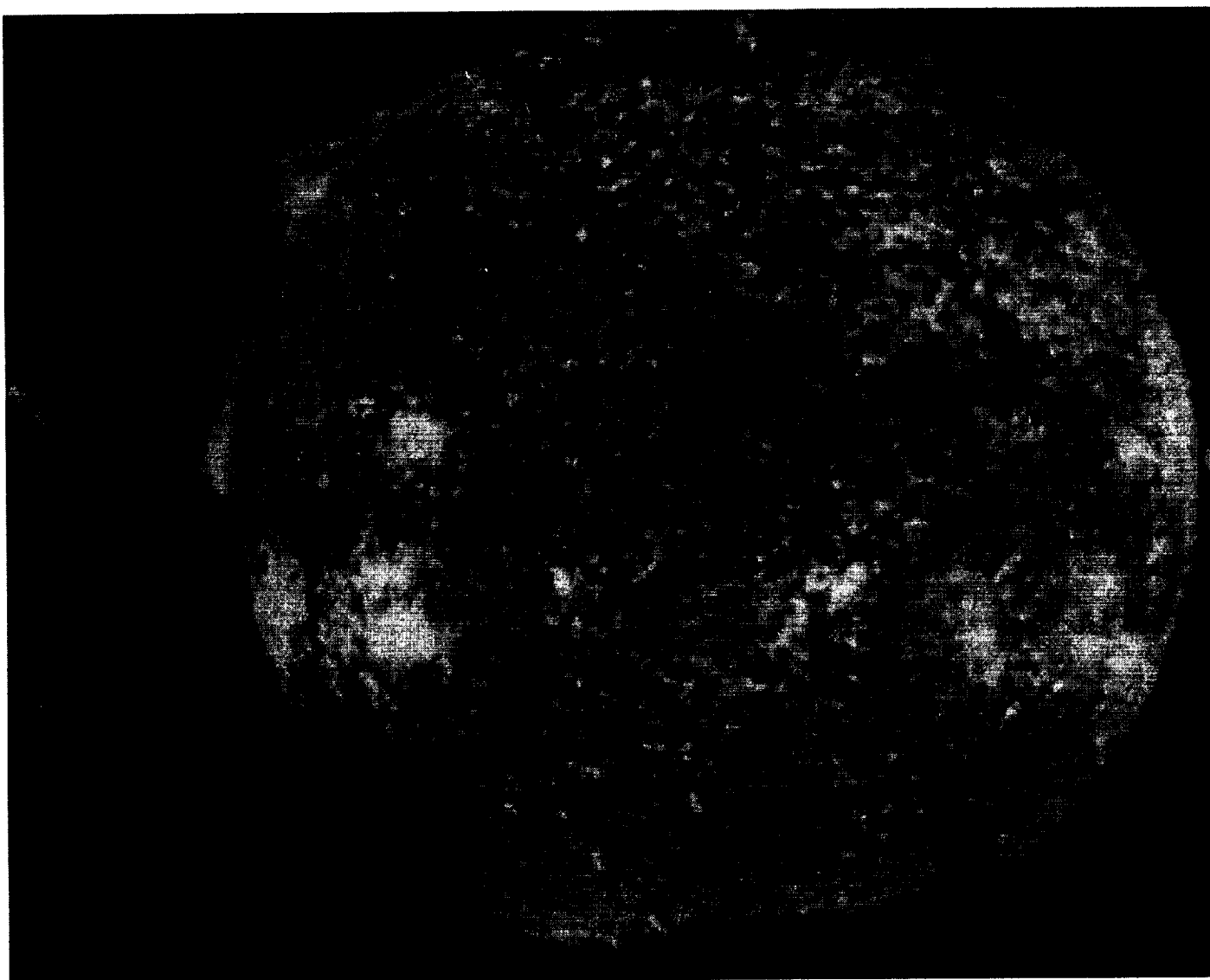
Spaceflight Radiation Health Program at the Lyndon B. Johnson Space Center

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A large solar prominence photographed by astronauts aboard Skylab

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SPACEFLIGHT RADIATION HEALTH PROGRAM AT LYNDON B. JOHNSON SPACE CENTER

INTRODUCTION

Early in the evolution of the space program, radiation was recognized as a hazard to humans traveling in space. Monitoring of crew radiation exposures was initiated during Project Mercury and has continued through the current Shuttle Program.

The space radiation environment is significantly different from that found terrestrially. Space radiation consists primarily of high-energy charged particles, such as protons, alpha and heavier particles, originating from several sources, including galactic cosmic radiation, energetic solar particles from solar flares and trapped radiation belts. Some of these high-energy particles inflict greater biological damage than that resulting from typical terrestrial radiation hazards. Crew exposures can easily exceed exposures routinely received by terrestrial radiation workers. Increased knowledge of the composition of the environment and of the biological effects of space radiation is required to assess health risks to astronaut crews.

Future expeditions into interplanetary space will place crews at increased risk of exposure compared to the current short duration low Earth orbit (LEO) missions. Long duration exploratory class missions will not benefit from the protection from galactic cosmic radiation (GCR) and energetic solar flare protons afforded by the Earth's geomagnetic field. Astronaut exposure to GCR within an unprotected or thinly shielded spacecraft during solar minimum is sufficient to exceed current astronaut exposure guidelines. Energetic solar particle events (SPEs) present an additional source of risk. These events are unpredictable in nature and potentially life threatening to an inadequately protected crew. Unshielded exposure to large solar particle events may lead to serious, acute health effects. To minimize the risk to the crew, the magnitude and dynamics of the potential

radiation environment must be considered when performing spacecraft and mission design.

For terrestrial radiation workers, additional protection against radiation exposure can be provided through increased shielding. Additional shielding against space radiation exposure may not be practical or efficient. Galactic cosmic radiation is extremely penetrating. Dose equivalent exposure rates behind thin shielding are reduced rapidly at first, but they plateau with increasing thickness. Thus, thicker shields become less efficient. The additional mass added purely for reducing radiation exposures becomes a substantial mass penalty for transportation vehicles and therefore may dramatically increase mission cost.

The Johnson Space Center (JSC) leads the research and development activities that address space radiation exposure and its effects on the health of astronaut crews. To assess these risks, increased knowledge of the environmental composition and the biological effects of space radiation is needed. Work at JSC covers a broad range of activity, beginning with the quantification of astronaut radiation exposures and extending to fundamental research into the biological effects of high-energy particle radiation exposure. In addition, the Spaceflight Radiation Health Program is working to achieve balance between the requirements for operational flexibility and the need to minimize crew radiation exposures.

ENVIRONMENTAL CHALLENGES

The radiation environment may be classified into three sources of radiation: trapped radiation, GCR, and SPE. Each source is characterized by a different composition of particle energies and fluence. Many of these sources are modulated during the course of the solar cycle.

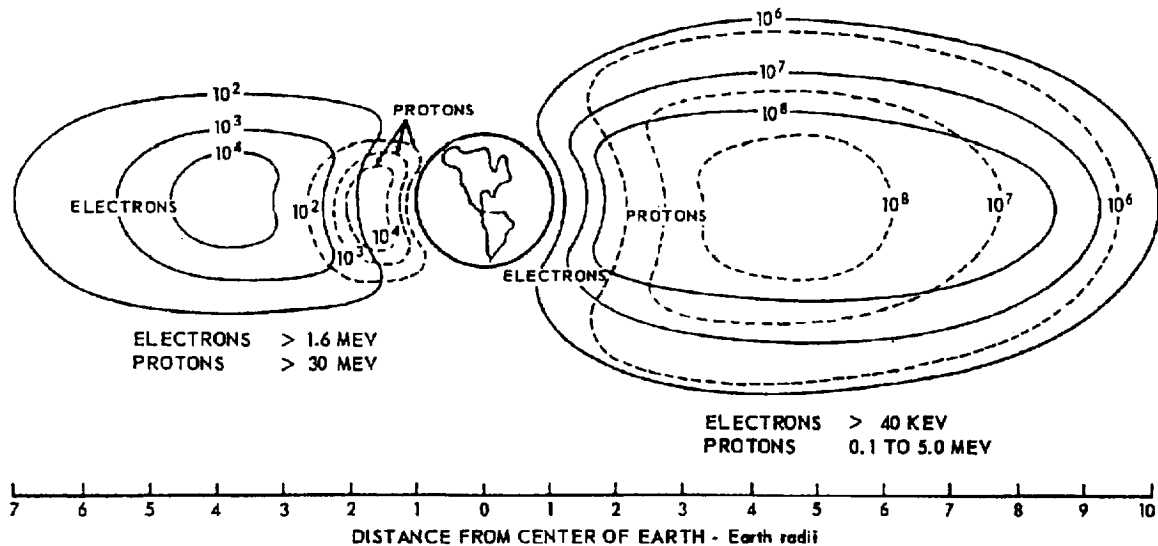


Figure 1. Trapped radiation belts as a function of energy and distance from the Earth.

Most manned spaceflight missions have been conducted within the protection of the Earth's magnetic field. The geomagnetic field shields the crews from large SPEs and a significant portion of the GCR. For the LEO missions, which have typified the U.S. manned space program, the largest fraction of the radiation exposure received has resulted from passage through a region known as the South Atlantic Anomaly (SAA). The remainder of the exposure is attributed to high-energy galactic cosmic radiation. During the Apollo lunar missions, astronauts traversed the trapped radiation belts into the unprotected realm of free space outside the geomagnetosphere. These excursions into cislunar space placed the astronauts at risk of receiving life-threatening radiation exposures if a large SPE were to occur. Fortunately, no major solar proton events occurred during these missions.

Trapped Radiation

The Earth's magnetic field is responsible for the formation of the trapped radiation belts that surround the Earth. Electrons and protons are trapped in regions starting above the atmosphere and extending to a distance of 10 to 12 Earth radii. Charged particles travel through these zones, spiralling around the

magnetic field lines and oscillating back and forth between "mirror points" located in opposite hemispheres. Figure 1 illustrates the distribution of high and low energy protons and electrons around the Earth.

The magnetic axis of Earth is tilted approximately 11 degrees from the spin axis and is slightly offset from the center of the Earth. As a result of the shift and tilt of the magnetic field, the trapped proton belts extend down to the atmosphere in the SAA region located over South America and the South Atlantic Ocean. Low inclination flights typically transit a portion of the SAA during six or seven consecutive orbits each day. Figure 2 shows the exposure rate as a function of orbital position for a 28.5-degree orbit. The SAA is the primary source of radiation exposure for the Shuttle and the proposed Space Station Freedom.

The proton spectra and fluence are strong functions of altitude. At the higher altitudes, the greater portion of crew exposures is received during transits through the SAA as a result of greater trapped proton fluence levels. At lower altitudes, the protons in the SAA interact with the residual atmosphere. Some of the protons are lost and contribute to an anisotropic distribution of protons. A greater than two factor difference exists between the proton flux from the east compared to the flux

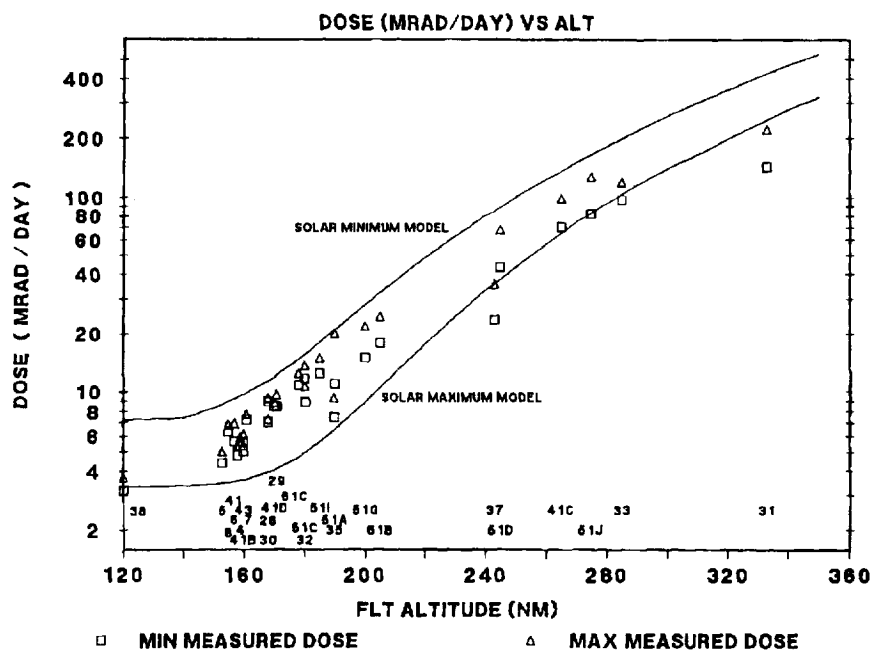


Figure 2. Absorbed dose to crew for 28.5 degree inclination Space Shuttle flights.

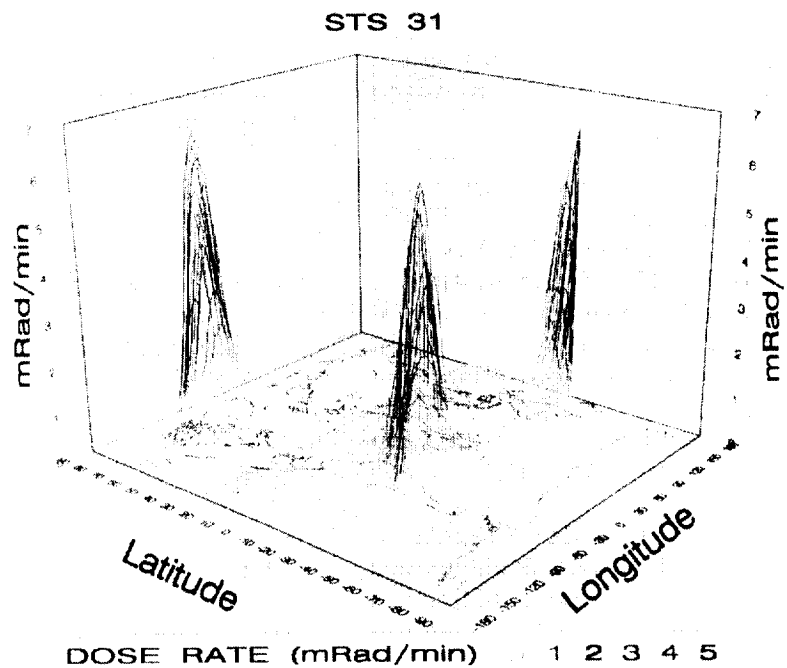


Figure 3. Absorbed dose rate as a function of position for a 28.5-degree inclination Shuttle flight.

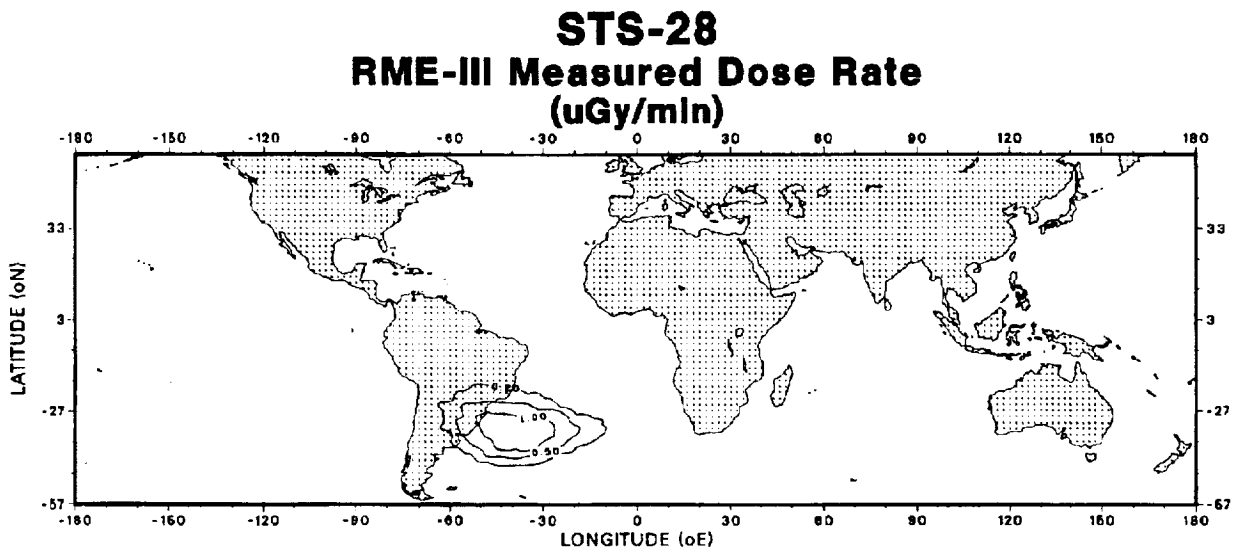


Figure 4. Dose rate measured within the Orbiter using the RME-III proportional counter during STS-28. Contours represent dose rates within the South Atlantic Anomaly.

from the west. The anisotropy in particle flux will be an important factor for Space Station.

In addition to altitude, the integrated dose is a function of orbital inclination and solar cycle. The dose received by the crew during low inclination (28.5 degree) LEO is illustrated in figure 3. The Space Station is planned to operate at this orbital inclination at 200 nautical miles (400 km). Increases in solar activity expand the atmosphere and increase the losses of protons in LEO. Therefore, trapped radiation doses in LEO decrease during solar maximum and increase during solar minimum.

Trajectories of low inclination flights do not pass the regions of maximum intensities within the SAA. Although high inclination flights pass through the SAA maximum intensity regions, less time is spent in the SAA than in low inclination flights. Thus crews in high inclination flights receive less net exposure to trapped radiation than in low inclination flights for a given altitude. This is

illustrated in figure 4, which depicts the location of the SAA as measured by internal equipment on the Shuttle. Low inclination flights will not transit the SAA south of 28.5 degrees south latitude. High inclination flights transit between north and south 58 degrees.

Galactic Cosmic Radiation

GCR originates from outside the solar system. It consists of ionized charged atomic nuclei from hydrogen (87%) and helium (12%) to uranium (trace) and are characterized by extremely large kinetic energies (up to several thousand GeV per atomic mass unit (amu)). The integral flux of four isotopes at solar minimum conditions is depicted in figure 5. These particles are distributed isotropically and found in relatively low fluence.

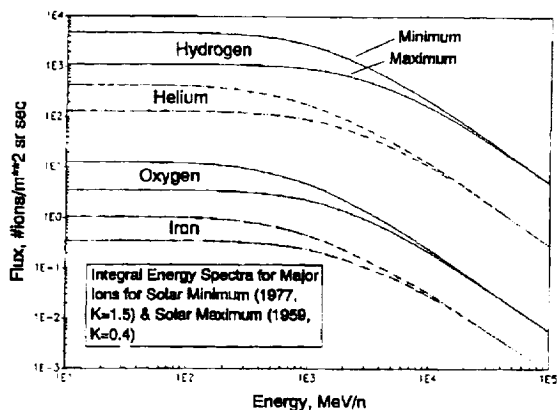


Figure 5. Integral GCR flux as a function of solar cycle.

The effect of solar activity on the integral GCR flux is also shown in figure 5. During periods of solar maximum activity, the interplanetary magnetic field generated by the Sun provides some protection to the inner solar system, decreasing GCR integral intensity. Higher energy particles are not appreciably attenuated; lower energy fluence is significantly reduced. The integral GCR dose rate in free space is approximately a factor of 2.5 higher at solar minimum than at solar

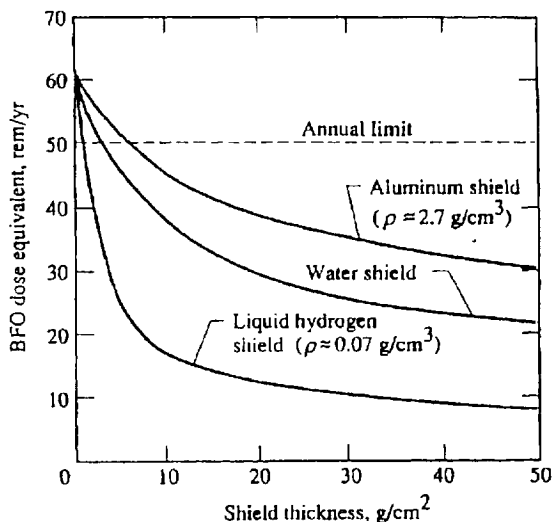


Figure 6. Shielding effectiveness of GCR at solar minimum.

maximum. During solar minimum, the unshielded dose to the blood-forming organs (BFO) is approximately 60 rem/year.

Due to its high energy, GCR is very penetrating. Thin to moderate shielding is effective in reducing the projected equivalent dose rate, but as shield thickness increases, shield effectiveness drops. This is the result of the production of a large number of secondary products, including neutrons from nuclear interactions between the GCR and shield nuclei. Figure 6 illustrates the annual BFO dose equivalent as a function of different shield materials.

The geomagnetic field also deflects many of the lower energy GCR components. This protection is primarily a function of latitude, as shown in figure 7. Compared to low inclination orbits, higher inclination orbits are exposed to increased GCR levels as the spacecraft transits the higher latitudes. In the proposed Space Station orbit, the magnetic field provides a factor of 10 reduction in total GCR exposure relative to the free space environment. During geomagnetic storms, higher GCR exposures may be experienced at lower latitudes. Little increase in GCR is realized as the altitude increases.

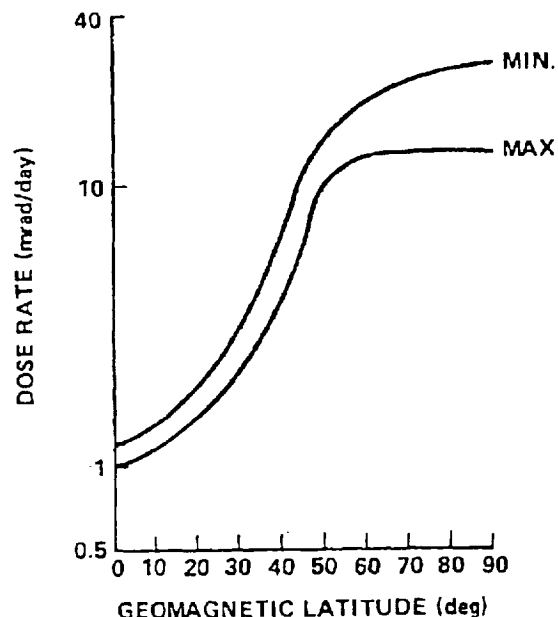


Figure 7. GCR dose rate as a function of latitude and solar cycle.

SOLAR PARTICLE EVENTS

SPEs are injections of energetic electrons, protons, alpha particles and heavier particles, into interplanetary space during solar flares. During periods of maximum solar activity, the frequency and intensity of solar flares increase. Most flares do not present a significant hazard because they are either too small to inject significant numbers of energetic solar particles, or they occur at solar longitudinal positions that are unfavorable for the direct transfer of particles to the Earth along interplanetary magnetic field lines. However, flares or rapid sequences of large flares that are orders of magnitude greater in intensity than most flares are of particular concern for generating very large, energetic SPEs. These solar proton events generally occur only once or twice a solar cycle. However, during the 22nd solar cycle, four comparable, extremely large flares occurred in a 4-month period. The October 19, 1989, event was the largest.

Each solar particle event is characterized by the total number of particles and the particle energy spectrum. The spectra of three of the largest proton events are depicted in figure 8. The intensity and spectral distribution of SPEs have a significant impact upon shield effectiveness. Figure 9 represents the shielding effectiveness for these large SPEs.

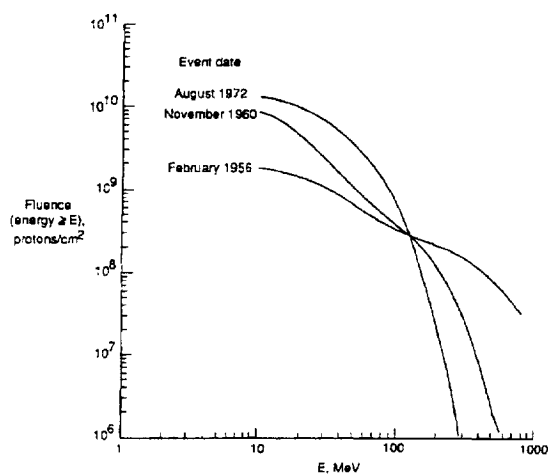


Figure 8. Spectra of three of the largest solar proton events.

Several factors make accurate prediction of SPEs difficult. First, solar flares occur without much warning. The magnitude and intensity of a flare are difficult to determine until the event is in progress. The directional emission of particles from the Sun further complicates predictions. Since SPEs are relatively directional, SPEs sensed by a terrestrial network may not threaten a Martian transit mission, and conversely, a flare injection of energetic solar particles that threatens a Martian transit mission may not produce particles at Earth.

SPEs pose the greatest threat to unprotected crews in polar, geostationary, or interplanetary orbits. To date, the greatest threat of significant exposures to astronauts existed during the Apollo Program. Figure 10 illustrates the variation in timing and magnitude of SPEs that occurred during the course of the Apollo Program. The calculated dose for crewmembers in the command module, in the lunar module, or in a space suit performing EVA is represented for each flare. As seen in the figure, it is only fortuitous that no significant SPEs occurred during the lunar missions.

Fortunately, most SPEs are relatively short-lived (less than 1 to 2 days), which allows for relatively small volume "storm shelters" to be feasible. To minimize exposure, the crew would be restricted to the storm shelter during the most intense portion

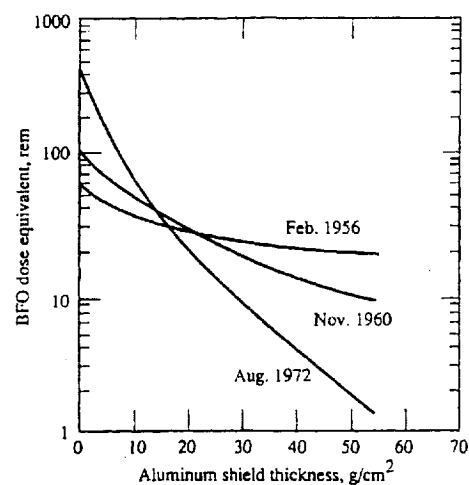


Figure 9. Shielding effectiveness for three of the largest solar proton events.

of the SPE, which may last for several hours. Storm shelters with shielding of 20 g/cm^2 or more of water equivalent material will provide sufficient protection for the crew.

Manmade Sources

Additional environmental hazards may be present from the use of manmade sources. These hazards may be in the form of exposure resulting from medical investigations, radioisotopic power generators, or small sources for experiments. Lunar and Martian missions may include either nuclear reactors for power or propulsion purposes that will contribute to crew radiation health concerns.

Low Earth Orbit Environment

Current missions are restricted to LEO. Figure 11 shows data taken during the high inclination STS-28 flight and illustrates the

contributions of the three natural sources of radiation. The GCR component varies cyclically with maximums at the extreme northern or southern portion of the orbital track. Minimums correspond to transits of the geomagnetic equator, where the spacecraft experiences the maximum geomagnetic protection from GCR. At periodic intervals large spikes in the exposure rates are encountered, which correspond to passages through the SAA. The largest spikes are passages through the regions of peak SAA intensity; smaller peaks represent passage through the fringes of the SAA. The effects of a solar particle event measured in LEO are a unique feature of these data. Peaks in the dose rate attributed to the SPE occur at the extreme northern or southern portions of the orbital track. While the GCR and SAA components shown in the figure are "typical" for high inclination flights, the effects of SPEs on dose rates will depend upon a variety of parameters.

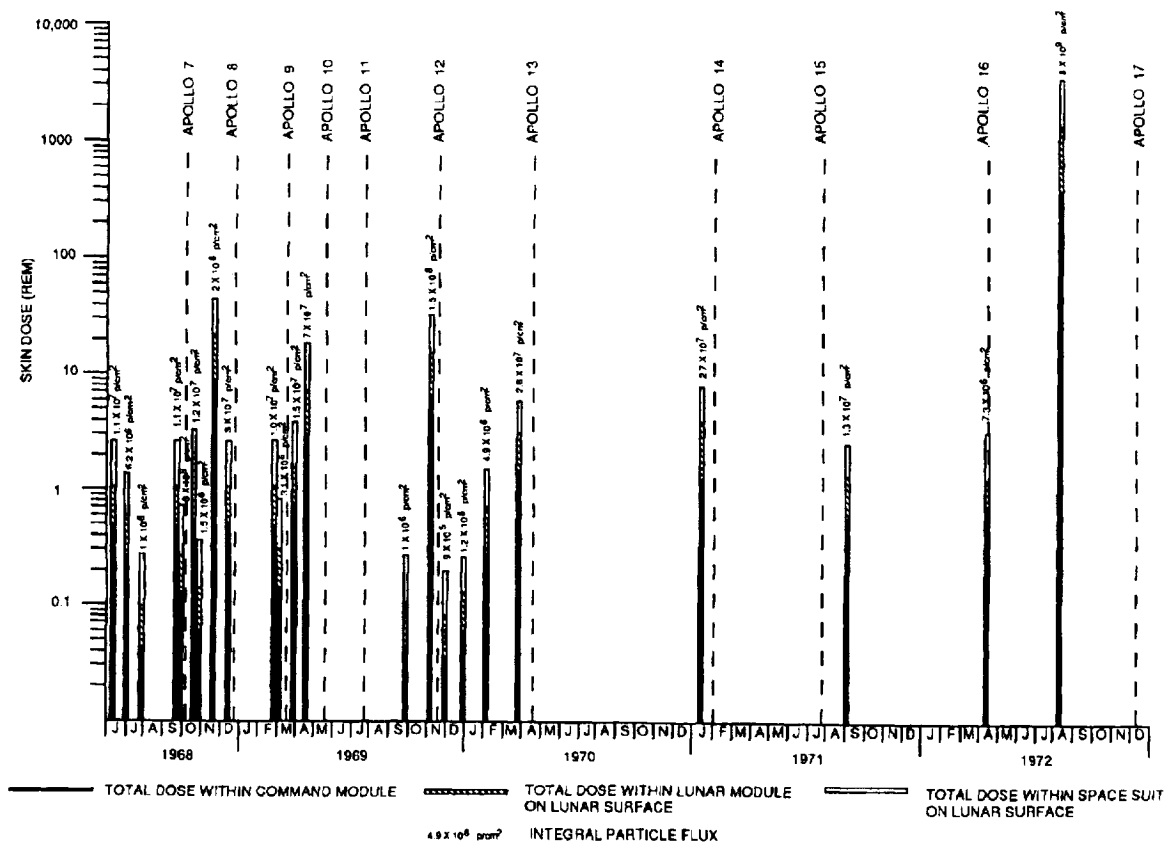


Figure 10. Solar proton events during the Apollo Program.

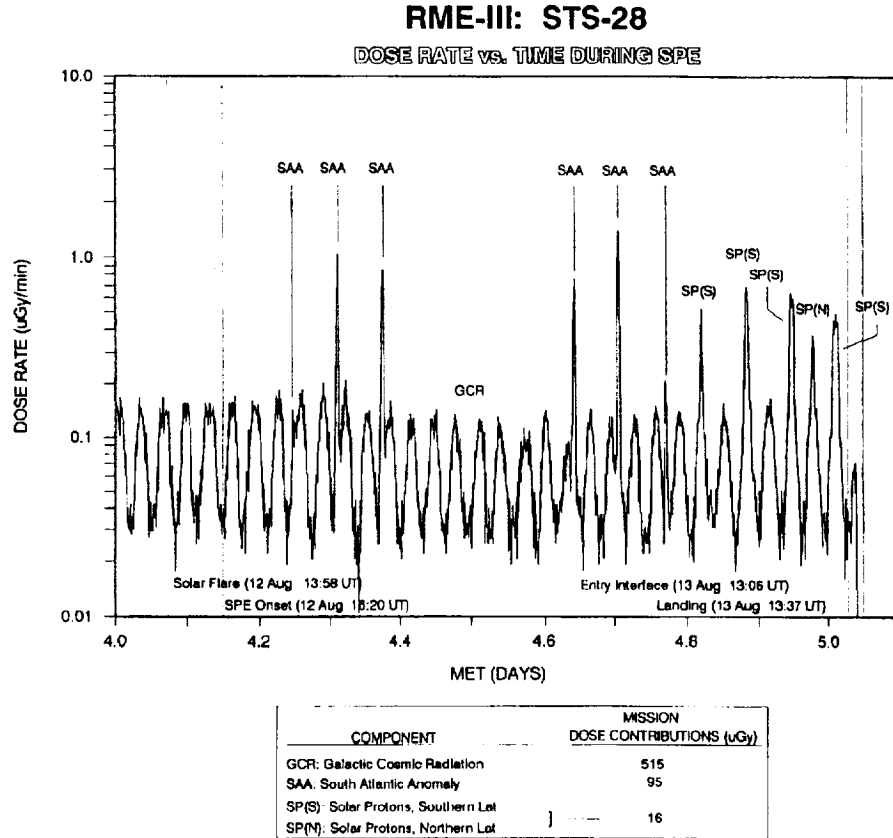


Figure 11. Measured dose rate vs. time for a high inclination Shuttle flight (STS-28). A large solar proton event occurred toward the end of the mission.

RADIATION PROTECTION ADMINISTRATION: LEGAL REQUIREMENTS

Astronauts have been classified as radiation workers; therefore, a program must exist to protect them from excessive radiation exposure. The Presidential Executive Order 12196 requires that all Federal agencies, including NASA, comply with Occupational Safety and Health Administration (OSHA) regulations related to ionizing radiation exposure. While NASA is required to follow OSHA regulations, no OSHA standards exist for spaceflight. Terrestrial radiation exposure guidelines provided in the Code of Federal Regulations (29 CFR 1910.96) are too restrictive for space activities, and, therefore, have been judged inappropriate. NASA can establish supplementary standards for appropriate control of radiation for astronauts

in accordance with 29 CFR 1960.18. Implementation of the supplementary standard requires that (1) its use applies to a limited population, (2) detailed flight crew exposure records are maintained, (3) preflight hazard assessment/ appraisal is performed, (4) planned exposures be kept as low as reasonably achievable, (5) operational procedures and flight rules are maintained to minimize the chance of excessive exposure, and (6) manmade onboard radiation exposure complies with 29 CFR 1910.96, except where the NASA mission/objectives cannot be accomplished otherwise.

NASA has adopted the recommendations that the National Council on Radiation Protection and Measurements (NCRP) presented in its Report 98, "Guidance on Radiation Received in Space Activities" (July 1989) as the basis for the supplementary standard for spaceflight crew radiation exposures. The maximum exposure limits are presented in Tables 1 and 2. While monthly and annual limits primarily exist to prevent the short-term physiological effects of exposure, career limits exist to contain radiation risk within a 3% increased lifetime cancer mortality. The recommendations of the NCRP apply to activities in LEO, such as Space Station. Astronaut exposure limits are greater than those of terrestrial radiation workers.

Recent information from reevaluation of

atomic bomb survivor data and other sources has provided impetus for further examination of the acceptable limits of astronaut radiation exposure. Preliminary recommendations from the NCRP evaluation of the new data suggest that even lower career limits for astronauts may be warranted.

During spaceflight, crew exposures are monitored using passive dosimeters. A new generation of radiation instrumentation is being developed to assist in interpreting the crew radiation exposures. Exposure from medical procedures and experiments are also determined for each astronaut. Records of exposure both to medical examinations and spaceflight are documented as part of the Spaceflight Radiation Health Protection Program.

TABLE 1. ORGAN SPECIFIC EXPOSURE LIMITS

EXPOSURE INTERVAL	DEPTH (5 CM)	EYE (0.3 CM)	SKIN (0.01 CM)
30 DAYS	25 REM	100 REM	150 REM
ANNUAL	50 REM	200	300
CAREER	100 TO 400	400	600

TABLE 2. CURRENT CAREER EXPOSURE LIMITS BY AGE AND SEX*

SEX	AGE			
	25	35	45	55
MALE	150 REM	250 REM	325 REM	400 REM
FEMALE	100	175	250	300

*The career depth equivalent dose limit is based upon a maximum 3% lifetime excess risk of cancer mortality. The total equivalent dose yielding this risk depends on sex and age at start of exposure. The career equivalent dose limit is approximately equal to:

200 + 7.5 (age - 30) rem for males up to 400 rem maximum

200 + 7.5 (age - 38) rem for females up to 400 rem maximum.

RADIATION HEALTH PROGRAM

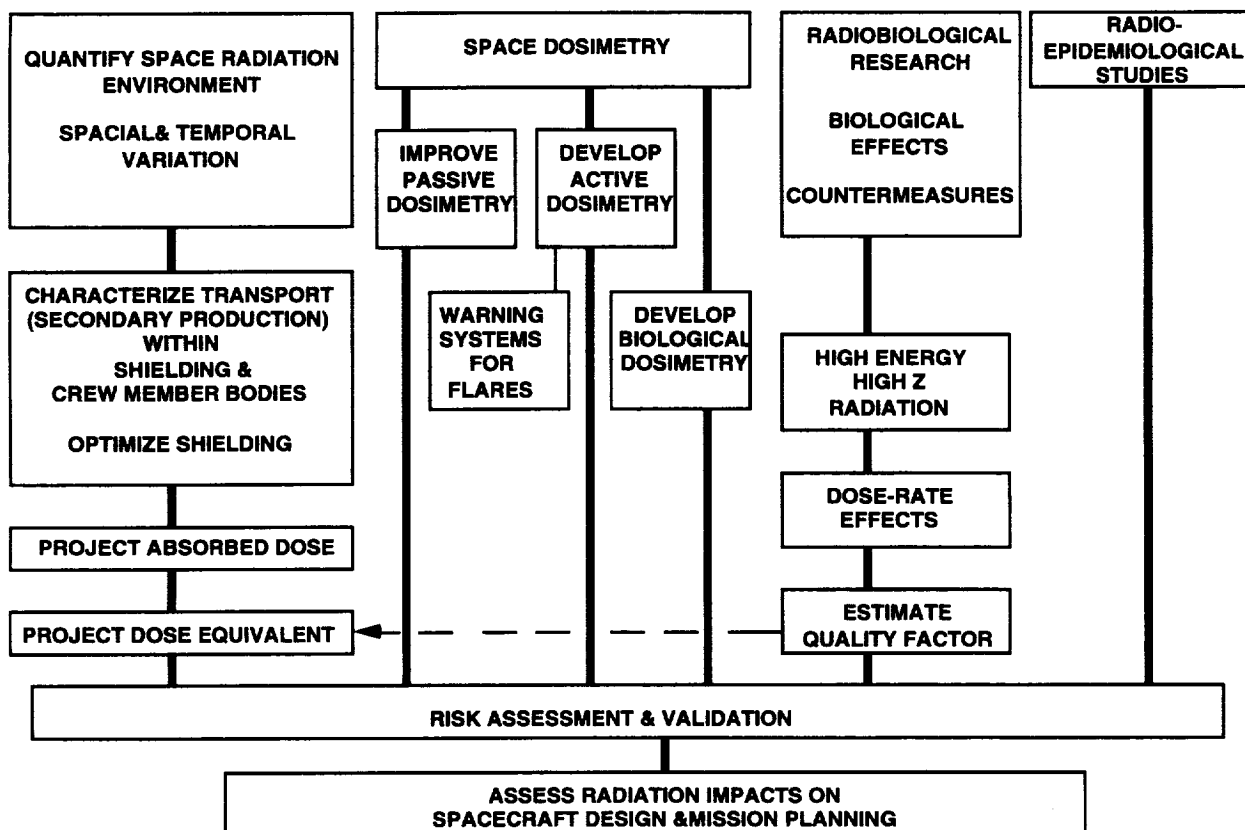


Figure 12. Areas of investigation within the Radiation Health Program.

RESEARCH AND DEVELOPMENT

Under the Space Radiation Health Program, NASA sponsors many investigations regarding space radiation research. Sponsored research typically falls into one of three categories: radiation physics, dosimetry, and radiobiology. An annual workshop for sponsored investigators is provided each year to discuss the achievements for the past year and direction of the upcoming year. The elements of the research program are illustrated in figure 12. Efforts at JSC address all three areas.

Advanced Radiation Monitors

Longer duration stays in the space radiation environment demand improved dosimetric instrumentation to evaluate the true health hazard to crews. The passive

dosimetry currently used for Shuttle missions provides only part of the information needed to quantify the crew effective dose equivalent. Two new instruments (TEPC and CPDS) are being developed for use on the Space Station to improve the crew radiation exposure risk estimation. These real-time instruments will continuously telemeter radiation data to Mission Control for monitoring the radiation environment. Prototypes of the new instruments are being tested during Shuttle missions. The new Space Station instrumentation includes:

Tissue Equivalent Proportional Counter (TEPC) -The TEPC, shown in figure 13, is a gas proportional counter that measures the linear energy transfer (LET) spectrum of the incident radiation in a simulated small volume of tissue. From the LET spectrum

and information provided in Report 60 of the International Commission on Radiological Protection (ICRP-60, 1990), the appropriate radiation quality factor can be estimated. The TEPC will be relocatable into any of the Space Station modules or nodes. The TEPC also is being modified and tested for potential flight opportunities with the Soviet Space Program. One version is planned for use on the Soviet space station Mir, and a second version is planned for inclusion as a radiation instrument on a probe to Mars. Other versions of the TEPC are being considered for routine use on commercial airline flights to assess the radiation dose from galactic cosmic radiation to the flight crews.

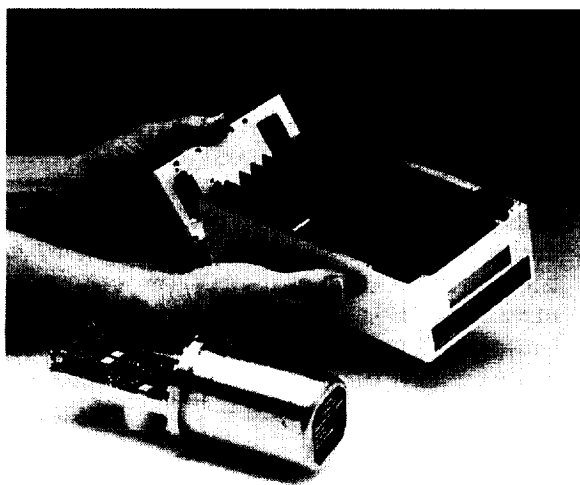


Figure 13. Tissue equivalent proportional counter (TEPC).

Charged Particle Directional Spectrometer (CPDS) - The CPDS will measure the flux of all trapped, galactic cosmic radiation and secondary radiation as a function of time, charge, energy, and direction. The CPDS is a semiconductor energy loss spectrometer. Incident radiation penetrates a stack of semiconductor wafers followed by a Cerenkov detector. The energy lost to each wafer is quantified and summed. Total particle energy and particle charge are deduced from these measurements. A 60-degree solid angle cone of acceptance of incoming radiation is achieved using coincidence circuitry and instrument geometry. Position sensitive detectors will provide

angular resolution of the incident radiation path within the detector. Two versions of the CPDS are planned: one for internal use and one for external use. The external instrument will consist of a single, fixed location unit with three independent detectors oriented in specific directions. The internal unit can be relocated within the Space Station modules or nodes. The external CPDS will collect data for accurate mapping of the space radiation environment, building improved crew dose projection tools and serving as a control for relocatable internal instruments. The internal CPDS will define the types of radiation inside the Space Station for assessing the penetration capability of the radiation. A prototype of the internal instrument is shown in figure 14.

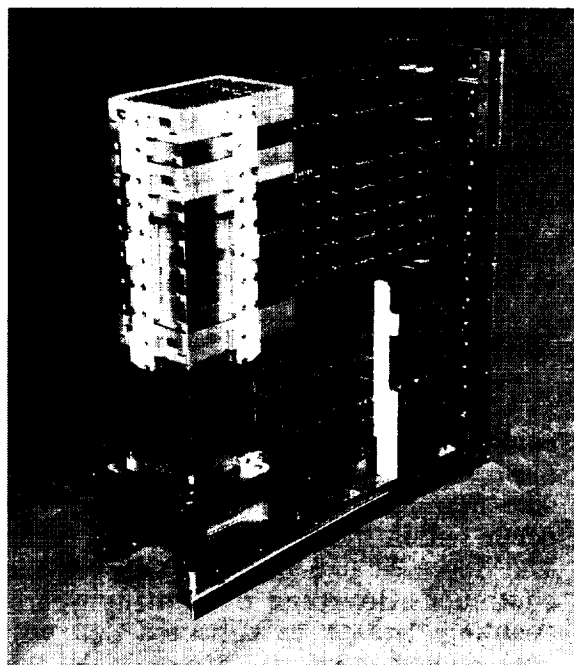


Figure 14. Charged particle directional spectrometer (CPDS).

Passive Dosimetry - Improved passive dosimetry, similar to that currently used on the Shuttle, will be used on Space Station. These include personal passive dosimetry for monitoring the absorbed dose to each astronaut and passive area monitors, which will be located at specific locations throughout the Space Station to measure the absorbed dose distribution.

Flight Experiment Support

Radiation flight experiments are frequently flown as part of the Shuttle Detailed Supplementary Objectives (DSOs) Program. These experiments include flight testing the radiation monitor prototype units as well as other monitoring devices.

Data from Space Station prototype spectrometers also have been used to assist investigations into Single Event Upsets (SEUs) in Shuttle computers. SEUs are events resulting from charged particles interacting within semiconductor devices that generate enough charge to change the state of flip-flop circuits, such as computer memory. These are known as "soft" upsets and can be corrected by reloading programs or data. "Hard" upsets result from physical damage to a circuit element from the incident radiation and are permanent.

Some medical procedures use radioactive tracers to track physiological changes as crewmembers adapt to the weightless environment. These hazards are reviewed by the Human Research Procedure and Protocol Committee. Crew doses are estimated for the procedures and documented in their health records.

Environmental Models

Current models of the trapped radiation environment (AP8, AE8) are over 20 years old. These are static models and do not take into account the dynamics that can occur within the trapped radiation belts. The Space Station platform will provide continuous coverage over many years, enabling data to be collected that will improve both the models and projections of crew doses. Data from the Space Station active monitors will be used to update and verify models of the trapped radiation environment as well as the cosmic radiation environment. Improvements will be incorporated in the models to accommodate transients as well as to correct for the physical shift of the SAA. Data gathered from prototype development flights have been used to provide a better understanding in the current structure of the LEO trapped radiation hazard.

Health Risk Assessment

The penetration of radiation within the body is being studied. Human equivalent densimetric phantoms are used to analyze the dose at different depths within the body. This information is correlated with transport codes and human anatomical computer models. These evaluations will lead to the ability of performing organ-specific dose estimates and of estimating the net increased risk of cancer for the crew.

Fundamental research into the effects of high-LET radiation also is performed at JSC. A variety of cell tissue cultures are irradiated with both on-site (gamma radiation, Co-60) and off-site (proton and heavy particle accelerators) sources. The transformation toward cancer within these samples is monitored, and the correlation of observed biological effects with received dose is determined. These types of studies are pivotal in the development of exposure standards for astronauts. Research in this arena may lead to the development of a biological dosimeter and/or counter-measures. Biological dosimeters will use biological media directly to measure biologically effective doses instead of relying on extrapolation from physical dosimeter measurements.

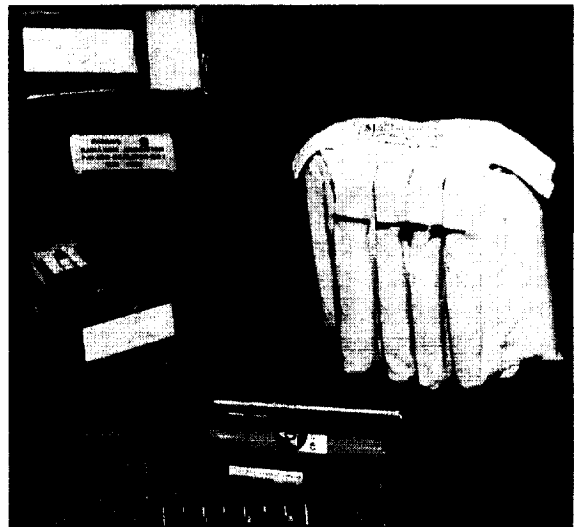


Figure 15. Space Shuttle Dosimetry.

MISSION SUPPORT: CREW EXPOSURE MONITORING

Monitoring astronaut radiation exposures has been a key requirement for spaceflight since Project Mercury. Current Space Shuttle operations require a variety of activities. Preflight activities include projecting mission doses and reviewing of crew health records. Dosimetry, shown in figure 15, for the crew and Orbiter are prepared and shipped to the Kennedy Spaceflight Center for integration into the Orbiter. During each mission, continuous radiological support and space environment monitoring are provided from within the Mission Control Center. Postflight, crew dosimetry is retrieved and analyzed and crew exposure records are updated. This process is depicted in figure 16.

Space Station operations will follow similar functional responsibilities. One of the most significant differences will be the

utility of real-time active radiation monitoring on the Space Station. This feature will provide significant improvement to operations by providing exposure monitoring during missions.

SUPPORTING ORGANIZATIONS

The Spaceflight Radiation Health Protection Program is administered from within the Space and Life Sciences Directorate. The general responsibilities of the respective divisions are summarized below.

Medical Sciences Division

- Support the mission Flight Surgeons in advising the Flight Director during radiation contingencies.
- Maintain astronaut health records including documentation of both mission and medical radiation exposure histories.
- Provide health risk analysis.
- Support payload safety reviews for Shuttle spaceflight experiments.
- Establish radiation health requirements for manned spaceflight.
- Provide integration support to Space Station; Develop radiological operational support training programs.
- Conduct and administer fundamental research into the biological effects of space radiation.

Solar System Exploration Division

- Provide real-time operational radiological support during manned missions.
- Provide operational dosimetry support for crews and manned vehicles.
- Provide preflight mission crew and equipment exposure projections.
- Improve and develop engineering tools used for space radiation exposure analysis.
- Develop advanced radiation monitoring equipment.

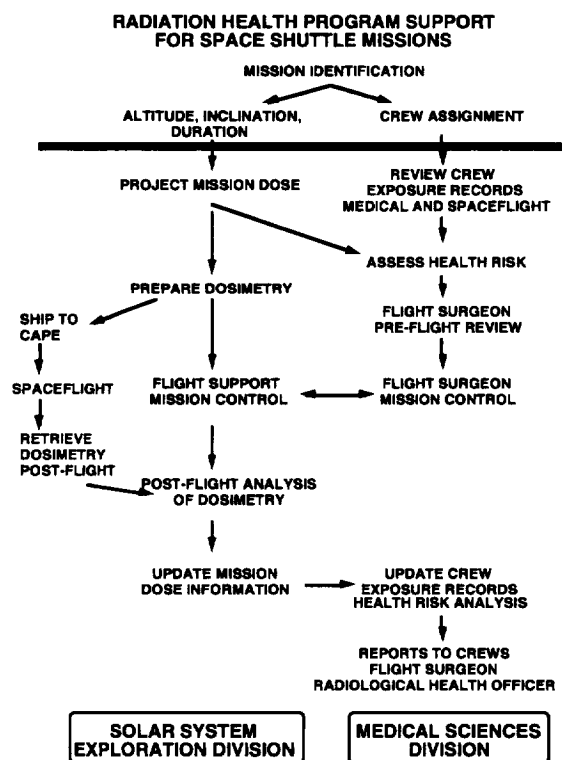


Figure 16. Space Shuttle support activities.

EXPLORATION OF MOON/MARS

As NASA plans for future missions to the Moon or Mars, radiation exposure remains one of the limiting technological issues. Random solar proton events were avoided during Apollo missions (Fig. 17) because of short mission duration. Future missions will involve longer stays, making simple avoidance less practical. Lunar stays of up to 6 months and round trip duration of 3 years for Martian missions are being considered. Accurate prediction of solar particle events still is not possible today. In addition, the biological effect from long-term exposure to high energy galactic cosmic radiation is not well understood. Current exposure guidelines will be exceeded unless adequate shielding is provided.

Nuclear technology may be used to enhance these missions, adding to the radiation protection concerns. Nuclear power plants on the lunar surface may be required to overcome the energy storage challenges resulting from 2-week duration lunar nights. Substantial savings in travel time and/or in propellant launched into orbit for Martian missions may necessitate the use of nuclear thermal propulsion. Although nuclear sources increase radiation risk to astronauts, overall mission reliability, success, and safety may be increased. JSC will be actively involved in these issues to ensure crew health.

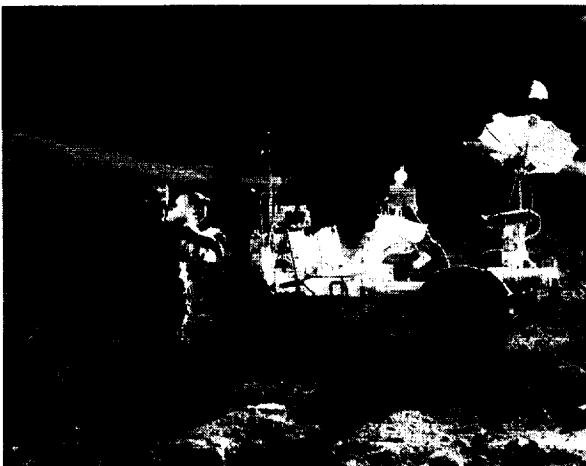


Figure 17. Apollo 17 astronaut on Moon with Lunar Rover.

SUMMARY

JSC is the focal point within NASA for crew radiation health protection. A comprehensive range of activities by JSC engineers and scientists, ranging from measuring biological effects to physical environmental model development, is being conducted to improve the quantitative understanding of risks to astronauts due to radiation exposure during spaceflight. Special instrumentation provides the means to quantify crew doses. Operational support for current missions and projected support for future exploration class missions will continue to be the function of the Spaceflight Radiation Health Protection Program at JSC.

DEFINITIONS

Several terms are frequently used to describe or quantify radiation exposure and are defined as follows:

RAD - The absorbed dose, RAD, is the amount of energy absorbed from radiation per mass of material (1 RAD = 100 ergs/g). The SI unit for absorbed dose is the Gray (1 Gray (Gy) = 100 Rad).

LET - Linear Energy Transfer quantifies the amount of energy deposited per unit length of particle track. This factor increases with the square of the charge and is inversely proportional to the energy of the radiation particle.

QUALITY FACTOR - Is a function of the particle LET, which is determined by the charge and energy of radiation particles. This factor accounts for the differences in biological effectiveness of different particles and is used to convert an absorbed dose into a dose equivalent. Currently, values for the quality factor may range from 1 to 20. Quality factor values as high as 100 may be deemed appropriate as additional research continues.

REM - The biological equivalent dose, REM (Roentgen equivalent man), is the absorbed dose adjusted for biological effectiveness of the particular type of radiation. It is the product of the absorbed dose and quality factor. The SI unit for biological equivalent dose is Sieverts (1 Sievert (Sv) = 100 Rem).

Rem = Rad X Quality Factor

Sievert = Gray X Quality Factor

eV - The kinetic energy of charged particles is measured in units of electron Volts (eV). Multiples of eV are frequently used:

keV = 1000 eV, MeV = 1,000,000 eV, and GeV = 1,000,000,000 eV.

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